

# A SPECIALLY DESIGNED AIR-ASSISTED SPRAYER TO IMPROVE SPRAY PENETRATION AND AIR JET VELOCITY DISTRIBUTION INSIDE DENSE NURSERY CROPS

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**ABSTRACT.** *New sprayers are needed to deliver droplets uniformly within dense nursery crops to obtain healthy and marketable plants in the nursery industry. An air-assisted sprayer with five-port nozzles was developed and investigated to improve spray penetration into dense nursery canopies. Spray deposits at the top, middle, and bottom of canopies were characterized using fluorescence detection, and were compared at three nozzle heights in a commercial nursery field. Dynamic air velocities corresponding to the deposit sampling locations inside and outside the canopy were measured at the time when the sprayer passed over the canopies. Air jet velocity profiles from nozzle outlets to 0.79 m below the nozzles were determined experimentally and mathematically. The measured air jet velocity decreased from 40.1 to 19.4 m/s when the distance from the orifice increased from 0.33 to 0.79 m. The peak velocities at the top and middle elevations for both inside and outside the canopy decreased as the nozzle height above the ground increased, but the peak velocities at the bottom elevation for both situations were not significantly decreased as the nozzle height increased. The average period of time for dynamic air velocities higher than 1 m/s inside the canopy was 1.9 s at the bottom, 3.8 s at the middle, and 1.1 s at the top of canopies. The mean spray deposit inside taxus canopies with leaf area index of 5.96 increased in an exponential function as the peak air velocity increased. The spray penetration capability and spray deposition uniformity inside taxus canopies were greatly improved with the five-port air-assisted sprayer.*

**Keywords.** *Dynamic air velocity, New sprayer, Nursery production, Pesticide, Spray deposition.*

Due to the large number of species in nursery production, commercially available sprayers have limited capacity for treating specific nursery species. To control insects and diseases inside dense nursery canopies, existing spray techniques have used either excessive or inadequate pesticide delivery to target areas, resulting in increased cost and contamination of the environment. Sprayers commonly used for field crops are unable to deliver sufficient pesticide to the inner or lower parts of dense nursery canopies, where insects and diseases frequently attack. In many cases, high application rates are used to increase the amount of pesticide deposited inside dense canopies, but the spray deposits at the top of the plants are saturated. Due to limitation of proper pesticide delivery systems

for dense nursery crops, large amounts of pesticide are wasted or improperly applied. Growers are seeking new sprayers or customized delivery systems that can operate economically and effectively with minimum canopy damage and optimum pest control.

To be marketable, many nursery plants are required to have full canopy shapes from the top to the bottom near the ground. Therefore, applying pesticides in nursery crops requires extra care. Some research on spraying nursery stock has been conducted, but the literature on results of spray trials is limited. Spray deposition within nursery crop canopies varies significantly with type of sprayers and plant species. Bache and Johnstone (1992) noted that more precise knowledge of fungicide coverage and plant canopy penetration is required to maximize effectiveness of chemical and biological crop management strategies. Krause et al. (2004) reported that spray deposition at different elevations in honey locust trees treated with a conventional axial-fan sprayer had much less variation than in Canadian hemlock trees treated with an over-the-row sprayer. Average spray deposit at the top of Canadian hemlock tree canopies was 14 times higher than that at the middle and the bottom of canopies, while about one-third of the total spray passed through the first row of honey locust trees with the axial-fan sprayer (Zhu et al., 1997). The tower sprayer with cross-flow fans provided less variation in vertical spray distribution in tree canopies than the traditional air-assisted orchard sprayers (Derksen et al., 2004).

Air-assisted sprayers are used widely to apply pesticide to trees and dense field crop canopies. The air jet deflects foliage and delivers spray droplets through the canopy,

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assisting droplet impingement on target foliage. To maintain air jet integrity in wind conditions and transport droplets uniformly throughout the plant foliage, adequate air volume is required in the canopy region. However, the mass flow rate of the sprayer jet at its outlet greatly influences the jet velocity distribution at considerable distances from the outlet (Reichard et al., 1979; Fox et al., 1982). The amount of spray delivered over a given distance is proportional to the power of the air stream (Fleming, 1962). Brazee et al. (1981) developed air jet models and concluded that air jets from low-velocity, high-airflow rate sprayers produced greater maximum velocities in the main region of the jets than higher-velocity, lower-airflow rate sprayers having equal air power at the outlet. Randall (1971) reported that a minimum air speed of 12.2 m/s was required for spray to penetrate beyond the outer canopy of apple trees.

Hydraulic nozzles, due to their simplicity, are widely used in the field applications for controls of weeds, insects, and fungi, but the deposition uniformity inside short, dense canopies is very poor (Zhu et al., 2004b). Air-assisted sprayers have potential to economically and effectively deliver pest control agents inside short, dense canopies without additional labor or machinery costs.

Zhu et al. (2004a) investigated a specially designed five-port air-assisted sprayer to improve spray penetration into canopies of taxus, a very dense nursery crop. The hypothesis of the sprayer design was that spray penetration into dense nursery crops can be improved by dividing a conventional large-diameter air jet into several small-diameter air jets arranged in a flat-fan shape. The small air jets can carry spray droplets deeper into dense canopies due to their high speed, and at the same time the adjacent air jets will create eddies to spread the droplets into surrounding areas within the canopy. Due to their flat-fan arrangement, the small air jets can cover a much wider spray width than a conventional large-diameter air jet. In contrast, a conventional large-diameter air jet may easily damage the part of the canopy directly beneath the single air jet outlet due to the high air volume and speed. The previous study (Zhu et al., 2004a) indicated that the five-port air-assisted sprayer improved spray penetration into taxus canopies. This study continued the concept of dividing a large air jet into several small-diameter air jets to form a flat-fan pattern to increase spray penetration and spray width for dense nursery crops.

The objectives of this research were to: (1) further investigate the five-port, air-assisted sprayer to improve spray penetration into short dense canopies by modifying nozzle design and changing nozzle heights, and (2) determine the relationship between spray deposits and air velocities at different levels within taxus canopies by changing the nozzle height above the top of canopy.

## MATERIALS AND METHODS

### FIVE-PORT SPRAYER

A boom-type, high-clearance, over-the-row sprayer (Hagie Manufacturing Co., Clarion, Iowa) was modified to become an air-assisted, high-clearance, over-the-row sprayer. The original boom-type hydraulic nozzles on the sprayer were converted to five-port, air-assisted nozzles. A hydraulic-driven centrifugal fan with 0.56 m diameter housing was mounted at 0.6 m above a trapezoid-shaped air distributor to

deliver air to the five-port air-assisted nozzles. The nominal fan speed was 9000 rpm. The centrifugal fan provided a high volume of airflow and high air pressure. The trapezoid-shaped air distributor served as a manifold between the fan and three five-port nozzles. Each nozzle was connected to the trapezoid air distributor with a 10 cm diameter pipe. The three five-port nozzles were mounted 0.61 m apart under the trapezoid distributor to direct fan pattern sprays covering a 1.82 m wide row of plants during spray application. The centrifugal fan, trapezoid-shaped air distributor, and three five-port nozzles were mounted on a metal frame to form a spray application system. A hydraulic motor was used to drive the metal frame to adjust the nozzle height. The pump and controller delivering liquid to the nozzles was the same as used for the boom-type spray system. The fan had high and low speed control with a hydraulic power switch. All controller switches were set inside the driver cab, with the spray application system mounted in front of the cab.

Each five-port nozzle consisted of an air manifold with five ports (Montana Industrials, Dal Negro, Brazil; distributed by Pickin' Patch, Inc., Plymouth, Ind.), and five liquid dischargers. The internal geometric construction of the five-port air manifold is shown in figure 1. The manifold was cast with five ports at 15° radial separation, each with an inside diameter of 3.6 cm.

The liquid discharger was a modified flat tip and was mounted at the centerline of each port of the five-port air manifold. The tip orifice was in the same plane as the port outlet. In the previous study (Zhu et al., 2004a), the liquid discharger at the center of each air port was 0.60 cm diameter copper tubing with a flattened outlet as its orifice. A precision orifice controlled total flow to the manifold that distributed liquid to each port. The design with the flattened-tubing orifice was simple, but it resulted in large variations in the spray pattern under each five-port nozzle. Liquid flow rate from individual ports was non-uniform, and the main spray stream from each port was not wide enough to cover the target

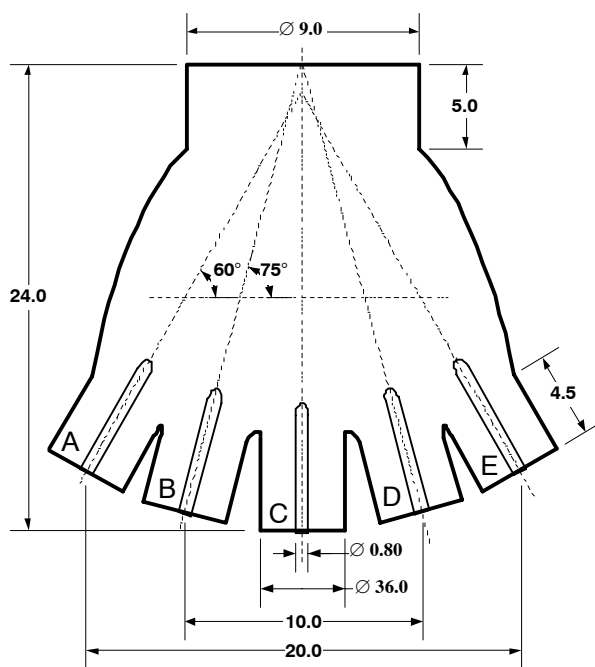


Figure 1. Internal structure of a five-port air manifold (dimensions in cm).



**Figure 2.** A modified liquid discharger for a five-port nozzle.

unless the nozzle height was sufficient. Increasing the nozzle height caused air velocity loss within the canopy and also increased drift potential.

In this study, the flattened tubing discharger was replaced with a modified flat fan tip to improve the accuracy of flow rate control and increase spray uniformity across the spray pattern width. The tip was modified from a brass tip, a part of a TeeJet 11003VB flat fan tip (Spraying Systems, Wheaton, Ill.), by reducing the exterior surface of the brass tip without changing the internal structure (fig. 2). The modified tip was 1.40 cm long with a 1.42 cm outside diameter. A 0.635 cm diameter by 9.5 cm long copper tube was bent to a 45° angle to connect the tip to the outer casting body of the five-port air manifold. The tubing was soldered to the modified tip with their centerlines aligned. With the modified liquid dischargers, liquid flow rates were discharged equally from the five ports, and the spray pattern across the 60 cm width, as determined by a portable spray patternator, became uniform 15 cm below the five-port nozzle.

#### FIELD TEST

Taxus (cv. L. C. Bobbink), a common dense nursery crop, was selected for evaluation of canopy penetration capability of the sprayer. At the time of the experiment, average plant height was 50 cm, average circumference was 196 cm, and edges of adjacent plants nearly overlapped. Spray deposits at three heights inside taxus canopies and three nozzle heights above the ground were evaluated with the air-assisted sprayer equipped with three five-port nozzles (fig. 3) in two trials. The three heights inside the canopies were 2.5, 25, and 46 cm above the ground, representing target positions at the bottom, middle, and top of the canopy, respectively. The three nozzle heights were 15, 25, and 35 cm above the top of the canopies, or 65, 75, and 85 cm from the orifice at the center port of each nozzle to the ground, respectively. The three five-port nozzles directed fan-pattern sprays downward toward three rows of taxus plants (fig. 3). The center port of each five-port nozzle was directly above the midline of each canopy row in a 1.8 m wide and 76 m long test plot.

A plot with three rows of taxus canopies was divided into nine sections to test the spray penetration with the three nozzle heights. The sprayer was operated at 140 kPa and 4.8 km/h travel speed from north to south. The total flow rate from each five-port nozzle at 140 kPa was 4.47 L/min, producing a 900 L/ha application rate for each test. A spray mixture containing water and Brilliant Sulfaflavine



**Figure 3.** Spray penetration test in a nursery crop, taxus field with an air-assisted sprayer containing three five-port nozzles.

(MP Biomedicals, Inc., Aurora, Ohio) at a concentration of 2 g/L was used for the two trials.

During the tests, the average wind velocity was 2.4 m/s for trial 1 on a sunny day and 1.1 m/s for trial 2 on a cloudy day. Wind direction was from south to north in both trials. In trial 1, the ambient temperature was 18°C and relative humidity was 39%. In trial 2, the ambient temperature was 16°C and relative humidity was 83%.

One canopy in each row of a section, a total of three canopies in each section, was randomly selected to locate artificial targets for collection of spray deposits. The targets were 2.5 × 7.5 cm sheet metal plates placed at the top (46 cm), middle (25 cm), and bottom (2.5 cm) of each canopy. Plates were mounted horizontally with their longer dimension normal to the stake and with 120° radial separation from each other. The midpoint of each plate was 11 cm from the stake. The stake was placed as near to the plant trunk as possible. The plates were collected 15 min after spraying and stored in 125 mL wide-mouth glass bottles in non-transparent boxes. These samples were stored in a refrigerator and analyzed within 24 h.

Spray deposits on sample plates were washed and dissolved in 20 mL of purified water (prepared with Mega-pure System, model MP-12A, Barnstead International, Dubuque, Iowa). Then a 4 mL sample solution was placed in a cuvette for determination of peak fluorescent intensity with a luminescence spectrometer (model LS 50B, Perkin-Elmer, Ltd., Beaconsfield, U.K.) at an excitation wavelength of 460 nm. If a sample concentration fell outside the calibration range, it was further diluted and measured again. Data were analyzed by one-way ANOVA, and differences among means were determined with Duncan's new multiple-range test using ProStat version 3.8 (Poly Software International, Inc., Pearl River, N.Y.). All significant differences were determined at the 0.05 level of significance.

#### STATIC AIR JET VELOCITY MODEL AND MEASUREMENT

A mathematical model was developed to calculate air jet velocities at the midline below each air port outlet (see Appendix A for details). The air velocity can be expressed by the following equation:

$$u_m(x) = \begin{cases} u_0, & x \leq 0.11 \\ \frac{0.211 \cdot u_0}{x + 0.1}, & x > 0.11 \end{cases} \quad (1)$$

To verify the accuracy of the air jet velocity model expressed by equation 1, static air velocity profiles at 40 points at locations ranging from the five-port nozzle outlets to 0.79 m below the middle port were measured inside a building. To determine the variation of air velocity from the three five-port nozzle system, air velocity at each port outlet for all three nozzles was measured. Points having air velocities over 45 m/s were measured with a No. 167 pitot tube (Dwyer Instruments, Inc., Michigan City, Ind.). Points having air velocities below 45 m/s were measured with an air velocity meter (model 8386A, TSI, Inc., St. Paul, Minn.). The sprayer was mounted over a concrete floor with the height of the center port 0.9 m above the floor. The fan was operated at 9000 rpm. The measured air velocities were converted to standard conditions, defined as 21.1 °C and 101.4 kPa at 0% relative humidity.

#### FIELD DYNAMIC AIR VELOCITY MEASUREMENT

To correlate canopy spray deposits to air speed, dynamic air jet velocities were measured at the bottom, middle, and top (or 2.5, 25, and 46 cm above the ground) inside a taxus canopy when the five-port air-assisted sprayer was passing over the canopy at the 4.8 km/h speed with three nozzle heights (15, 25, and 35 cm) above the canopy. The three air velocity probes were constant temperature anemometer (CTA) sensors (0.15 mm cylindrical, hot-film; model 1210-60, TSI, Inc., St. Paul, Minn.) located at the three elevations inside the canopy and controlled by an anemometer (model 1050B, TSI, Inc.). Each CTA sensor was enclosed in a screen guard to protect it from damage by moving foliage.

Output signals from the anemometer were recorded with a 14-channel magnetic tape recorder (model 3500, Sangamo Electric Co., Springfield, Ill.). The CTA sensors at three elevations inside the taxus canopy were positioned at different distances from the canopy main stem in the plant row centerline so they would not interfere with each other. The sensors were calibrated with a calibrator (model 1125, TSI Inc.). After air velocity signals were recorded on magnetic tape in the field, a data acquisition board (model KPCI-3108, Keithley Instruments, Inc. Cleveland, Ohio) was used in the laboratory to convert the analog velocity signals from the magnetic tape to digital format, which was acquired and stored at a rate of 2,000 samples per second.

In order to compare air velocities at three levels inside the canopy, velocities at the same levels were measured outside the canopy with the three CTA sensors as the sprayer passed over the sensors for each of the three nozzle heights used. Air velocity measurement for every condition was repeated five times. During measurement in the field, the average wind velocity was 2.2 m/s from the south, the ambient temperature was 14 °C, and relative humidity was 85%.

Because dynamic air jet velocity data were acquired at a rate of 2,000 samples per second and measurement was repeated five times for every condition in the field, it was impossible to have identical air velocity profiles for the five

replications. A method was devised to obtain an averaged air-velocity transience (pulse) for the five air velocity profiles inside and outside the taxus canopy as the sprayer passed over the CTA sensors (see Appendix B for details).

#### LEAF AREA INDEX MEASUREMENT

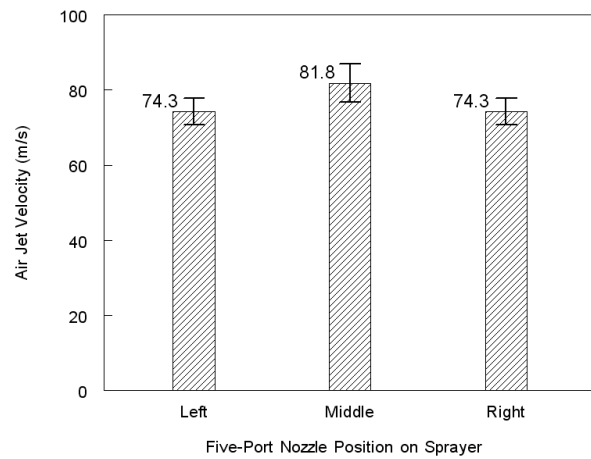
Following the measurement of dynamic air velocities inside the canopy, leaf area index (LAI) of three taxus canopies were measured using an LAI-2000 plant canopy analyzer (LI-COR, Inc., Lincoln, Neb.) with two sensor modes. The instrument recorded the attenuation of diffuse sky radiation at five angles simultaneously as it passed through the canopy and gave an estimate of the amount of foliage in the canopy per unit ground area. A dimensionless unit was used for leaf area index, which was m<sup>2</sup> foliage area/m<sup>2</sup> ground area. Due to market requirements, all taxus canopies are trimmed to retain a uniform shape and size every year. Three canopies were randomly selected from those used in the spray deposition tests. Before the measurement, about 10 cm of soil and debris were removed beneath each canopy for the convenience of positioning the lower optical sensor close to the bottom of the canopy. The upper sensor was set about 1.2 m above the ground. Both sensors were leveled. For each canopy, eight measurements of LAI at eight orientations in an octagon shape were conducted. The sky was fully covered by clouds at the moment of measurement. The LAI sensor was also calibrated under fully cloudy conditions.

## RESULTS AND DISCUSSION

#### STATIC AIR JET VELOCITY FROM AIR PORT

The average axial air jet velocity near the outlets of the five-port nozzles was 81.8 m/s for the middle five-port nozzle, and 74.3 m/s for both the left and right nozzles under the trapezoid air distributor (fig. 4). The average outlet velocity from the middle nozzle was about 9% higher than that from the two adjacent nozzles. Unequal air paths from the distributor to the three nozzles might have caused the variation in mean velocities from the three five-port nozzles, as the middle nozzle was closer to the manifold than the two side nozzles. However, the variation in exit air velocity for the five ports on each individual five-port nozzle was very low. For example, the standard deviations of the outlet velocity from the five ports on the left, middle, and right five-port nozzles were 3.6, 5.1, and 3.5 m/s, respectively. The variation in air jet velocities near the three five-port nozzle outlets was about 6%. Therefore, the sprayer produced reasonably uniform air output from each of the three nozzles.

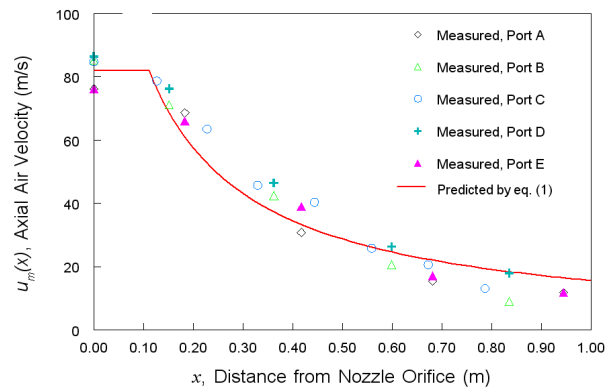
Air velocities across the fan pattern at the same distance from the nozzle outlets were not consistent because the five air jets were separately discharged from the five ports on each nozzle (fig. 5). For example, the average midline air velocity from the five ports of the nozzle was 40.9 m/s at 0.33 m downstream from the nozzle, while the average velocity across the fan pattern was 33.4 m/s at 0.33 m distance. The difference between the two average velocities decreased as the downstream distance from the nozzle increased. For example, the difference between the two average velocities was about 1.9 m/s at 0.56 m from the nozzle, and 0.7 m/s at 0.79 m from the nozzle. Except for one measurement, air velocities across the level at 0.79 m from the nozzle were nearly constant. Therefore, variations in air velocities across



**Figure 4.** Average air jet velocity near outlets of five ports for three nozzles, 0.61 m apart, located at the left, middle, and right in front of the sprayer. Error bars represent standard deviations of means.

the same level above the ground decreased as distance from the nozzle increased.

Figure 6 shows a comparison of experimentally determined axial air velocities at various distances from the nozzle orifice with values predicted by equation 1 with an assumption of  $u_0 = 81.8$  m/s, which was the average of the outlet velocities from the five ports of the middle nozzle under the trapezoid air distributor. The calculated air jet velocity from equation 1 agreed very well with the measured velocity. The slope of the linear regression equation for the calculated and measured velocities was 1.08, with  $r^2 = 0.98$ . An equilateral hyperbola relationship was used to represent the midline air velocity in the jet's main region as a function of distance from the port outlet. The air jet velocity decreased as the distance from the port outlet increased due to jet entrainment,



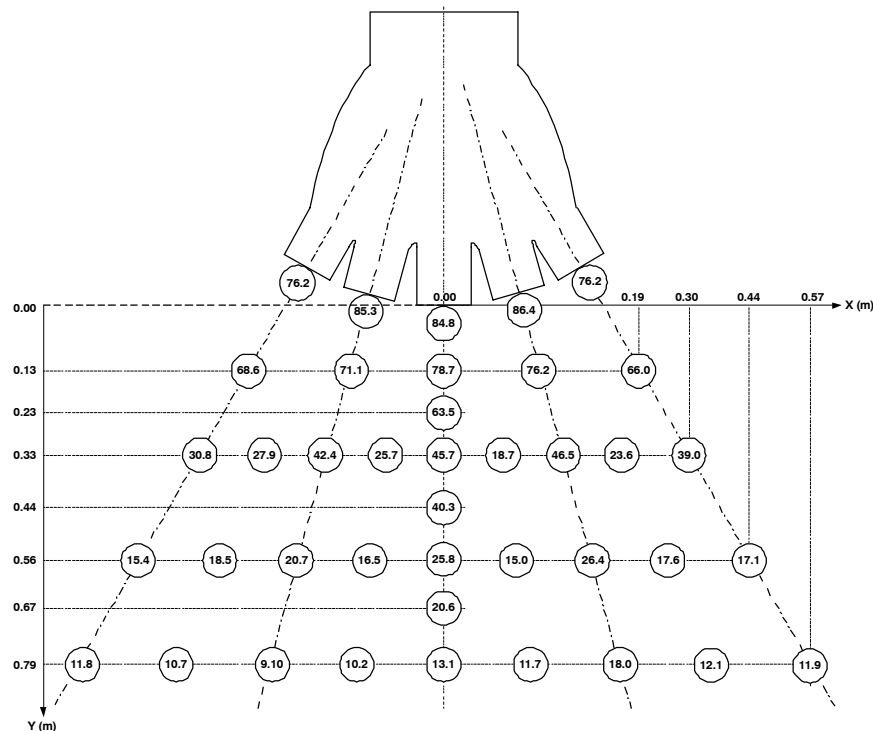
**Figure 6.** Comparison of measured and calculated axial air velocities at different distances from the five outlets of the five-port nozzle.

divergence, and turbulent dissipation. For example, the air velocity decreased from 40.1 to 19.4 m/s (51.3%) when the distance from the port outlet increased from 0.33 to 0.79 m. In field conditions, the air velocity profiles differed from that measured under indoor conditions, as discussed in the following section.

#### DYNAMIC AIR VELOCITY PROFILE INSIDE AND OUTSIDE THE TAXUS CANOPY

Instantaneous air velocity profiles at the bottom, middle, and top locations inside the taxus canopy (fig. 7) and outside the canopy (fig. 8) appeared as pulse transients when spray nozzles mounted 25 cm above the canopy passed over the sensors at a travel speed of 4.8 km/h. Duration of velocity transients inside the canopy was shorter than outside the canopy.

Calculated with equation 12 in Appendix B, data in table 1 show average peak air velocities inside and outside the



**Figure 5.** Axial air velocities at positions below the five outlets of the five-port nozzle. Values in circles are air velocities in m/s.

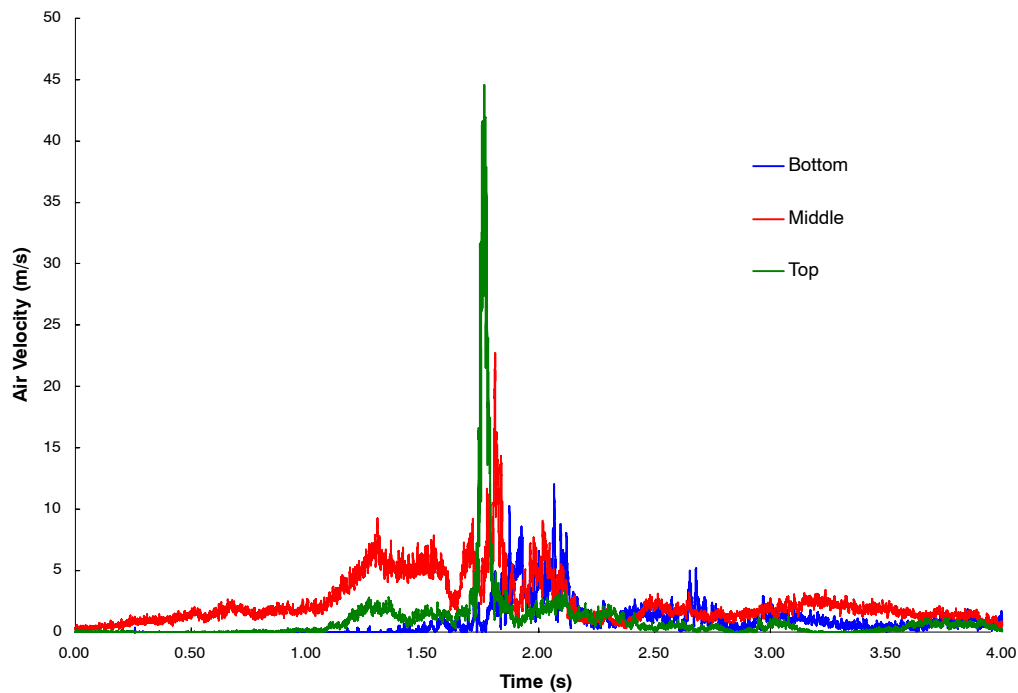


Figure 7. Real-time instantaneous air velocity profiles at the top, middle, and bottom of a taxus canopy when the sprayer with the nozzle height 25 cm above the canopy passed over the canopy at 6.4 km/h.

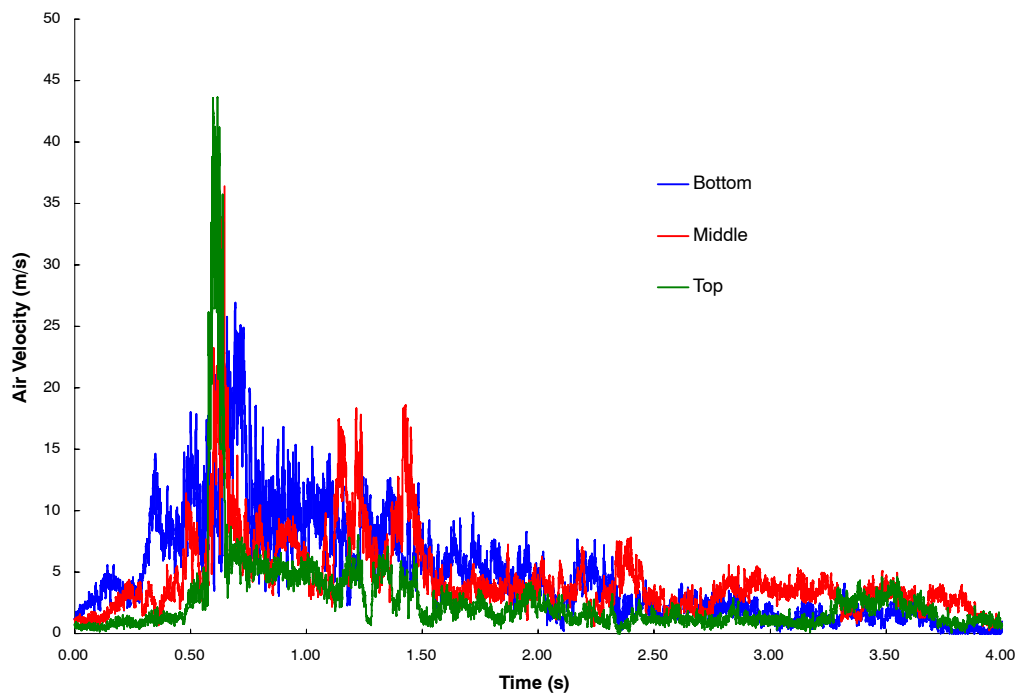


Figure 8. Real-time instantaneous air velocity profiles at three different heights outside the canopy when the sprayer with the nozzle height 25 cm above the canopy passed over the CTA anemometer sensors at 6.4 km/h.

canopy at the bottom, middle, and top locations when spray nozzles mounted at 15, 25, and 35 cm above the canopy passed over the sensors at 6.4 km/h. The average peak velocities at three heights inside the canopy were considerably lower than the velocities at the same heights outside the canopy for all three nozzle heights. The peak velocities at the top and middle elevations for both inside and outside the canopy decreased as the nozzle height above the ground increased. However, the peak velocities at the bottom elevation for both

situations did not drastically decrease as the nozzle height increased. Due to interception of airflow by dense canopies, rates of decrease in peak velocities from top to middle and bottom locations inside the canopy were considerably higher than outside the canopy. When the nozzle height was 15 cm above the canopy, the peak air velocities decreased 4.9 times from top to bottom inside the canopy, and 1.8 times from the top to middle. For the same conditions, the peak air velocities outside the canopy decreased 2.1 and 1.2 times, respectively.



**Table 1. Average peak air velocities calculated from equation 12 at three different heights inside and outside the canopy when the sprayer passed over sensors with three different nozzle heights above the canopy. Standard deviations are given in parentheses.**

Sensor Height (cm)	Nozzle Height (cm)	Air Velocity (m/s)		
		Outside Canopy	Inside Canopy	Ratio
2.5 (bottom)	15	30.6 (6.8)	10.1 (2.8)	3.0
	25	27.8 (4.2)	10.0 (1.9)	2.8
	35	26.6 (2.3)	7.9 (1.1)	3.4
25 (middle)	15	56.1 (8.1)	28.0 (11.6)	2.0
	25	48.3 (8.0)	21.1 (2.6)	2.3
	35	42.6 (11.0)	17.9 (3.9)	2.4
46 (top)	15	65.7 (6.2)	49.7 (11.7)	1.3
	25	53.8 (12.5)	42.7 (4.3)	1.3
	35	50.9 (5.5)	36.2 (8.1)	1.4

The average peak air velocity at the bottom of the canopy was 9.3 m/s for the three nozzle heights when the air jet velocity near the port outlets was 81.8 m/s. The velocity decreased 8.8 times from the nozzle outlet to the bottom of the canopy. The taxus canopies acted as a porous filter function in degrading air velocity.

The taxus plant has one of the densest canopies in nursery production. The average leaf area index of the taxus canopies during the test was 5.93. With this value of leaf area index, the ratios of air velocities at the top and bottom inside the canopy were 5, 4.3, and 4.6 for nozzle heights of 15, 25, and 35 cm above the canopy, respectively. The average peak air velocity at the bottom location outside the canopy for the three nozzle heights was three times the velocity at the same height inside the canopy. Therefore, the peak air velocity at the bottom of the canopy was reduced three times due to the interception by the dense canopies with a leaf area index of 5.93.

Data in table 2 show the period of time that air velocities at three heights inside and outside the canopy were higher than 1 m/s when the sprayer passed over the sensors using three different nozzle heights. Equation 18 in Appendix B was used to average the velocity profiles from five replications to determine the time period for each treatment. At the three nozzle heights, the average time period for air velocities higher than 1 m/s inside the canopy was 1.9 s at the bottom, 3.8 s at the middle, and 1.1 s at the top of the canopy, respectively. With the same conditions, the average period of time outside the canopy was 3.6 s at the bottom, 4.6 s at the middle and 2.9 s at the top, respectively. The airflow inside the canopy degraded faster than that outside the canopy.

## SPRAY DEPOSITION

In the two trials, spray deposits at the top of canopies were not significantly different for the three nozzles on the sprayer and were not significantly different in most cases for the three nozzle heights with two trials (table 3). This result was true for spray deposits at both the middle and bottom of the canopies (tables 4 and 5). Therefore, the three five-port nozzles could deliver equal amounts of spray deposit into the canopies, although there was about 6% variation in air jet velocities near the three five-port nozzle outlets (fig. 9). Figure 9 shows that average spray deposits at the bottom, middle, and top inside canopies were: 0.143, 0.358, and 0.718  $\mu\text{L}/\text{cm}^2$  for the nozzle height of 15 cm above the canopy; 0.127, 0.165, and 0.635  $\mu\text{L}/\text{cm}^2$  for the nozzle height of 25 cm above

**Table 2. Period of time that air velocities at three different levels within a canopy was higher than 1 m/s when the sprayer was passing over the canopy at three different nozzle heights above the canopy.**

Sensor Height (cm)	Nozzle Height (cm)	Period of Time (s)	
		Outside Canopy	Inside Canopy
2.5 (bottom)	15	3.61	1.56
	25	3.87	2.57
	35	3.47	1.65
25 (middle)	15	3.88	3.81
	25	5.31	3.82
	35	4.76	3.80
46 (top)	15	2.57	0.69
	25	3.50	1.65
	35	2.59	1.01

**Table 3. Mean spray deposits at the top of taxus canopies (46 cm height inside canopies) with three five-port nozzles in two trials when the nozzle discharge heights above the top of canopies were 15, 25, and 35 cm. All values in  $\mu\text{L}/\text{cm}^2$  (standard deviations in parentheses).<sup>[a]</sup>**

Trial	Nozzle	Nozzle Discharge Height		
		15 cm	25 cm	35 cm
1	Left	0.78 (0.32) aA	0.92 (0.45) aA	0.20 (0.30) aA
	Middle	0.89 (0.55) aA	0.47 (0.47) aA	0.56 (0.14) aA
	Right	0.79 (0.71) aA	0.63 (0.22) aA	0.71 (0.41) aA
2	Left	0.58 (0.50) aA	0.86 (0.42) aA	0.63 (0.44) aA
	Middle	0.56 (0.24) aA	0.42 (0.04) aA	0.88 (0.42) aA
	Right	0.70 (0.14) aAB	0.51 (0.07) aA	0.97 (0.19) aB

<sup>[a]</sup> Means in a row followed by different uppercase letters are significantly different ( $p < 0.05$ ). Means in a column followed by different lowercase letters are significantly different ( $p < 0.05$ ).

**Table 4. Mean spray deposits at the middle of taxus canopies (25 cm height inside canopies) with three five-port nozzles in two trials when the nozzle discharge height above the top of canopies was 15, 25, and 35 cm. All values in  $\mu\text{L}/\text{cm}^2$  (standard deviations in parentheses).<sup>[a]</sup>**

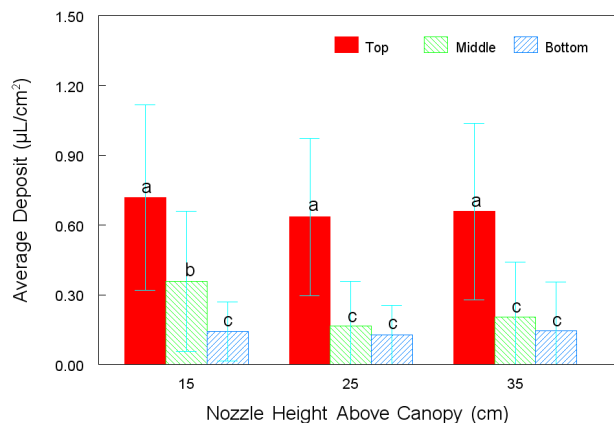
Trial	Nozzle	Nozzle Discharge Height		
		15 cm	25 cm	35 cm
1	Left	0.58 (0.61) aA	0.09 (0.08) aA	0.26 (0.33) aA
	Middle	0.22 (0.12) aA	0.20 (0.20) aA	0.26 (0.14) aA
	Right	0.65 (0.16) aA	0.24 (0.17) aB	0.16 (0.07) aB
2	Left	0.21 (0.16) aA	0.03 (0.02) aA	0.07 (0.05) aA
	Middle	0.17 (0.11) aA	0.16 (0.12) aA	0.14 (0.11) aA
	Right	0.33 (0.10) aA	0.27 (0.40) aA	0.35 (0.48) aA

<sup>[a]</sup> Means in a row followed by different uppercase letters are significantly different ( $p < 0.05$ ). Means in a column followed by different lowercase letters are significantly different ( $p < 0.05$ ).

**Table 5. Mean spray deposits at the bottom of taxus canopies (2.5 cm height inside canopies) with three five-port nozzles in two trials when the nozzle discharge height above the top of canopies was 15, 25, and 35 cm. All values in  $\mu\text{L}/\text{cm}^2$  (standard deviations in parentheses).<sup>[a]</sup>**

Trial	Nozzle	Nozzle Discharge Height		
		15 cm	25 cm	35 cm
1	Left	0.17 (0.15) aA	0.23 (0.18) aA	0.30 (0.26) aA
	Middle	0.19 (0.13) aA	0.26 (0.14) aA	0.21 (0.22) aA
	Right	0.22 (0.21) aA	0.07 (0.08) aB	0.01 (0.00) aA
2	Left	0.08 (0.03) aA	0.08 (0.05) aB	0.09 (0.10) aA
	Middle	0.05 (0.03) aA	0.10 (0.07) aB	0.24 (0.36) aA
	Right	0.15 (0.15) aA	0.02 (0.01) bA	0.02 (0.01) aA

<sup>[a]</sup> Means in a row followed by different uppercase letters are significantly different ( $p < 0.05$ ). Means in a column followed by different lowercase letters are significantly different ( $p < 0.05$ ).



**Figure 9.** Average spray deposits at the top, middle, and bottom of taxus canopies with three different nozzle heights above the ground. Lowercase letters represent significant difference ( $p < 0.05$ ) among spray deposits at three heights inside canopies and three nozzle heights. Error bars represent standard deviations of means.

the canopy; and 0.146, 0.206, and 0.659  $\mu\text{L}/\text{cm}^2$  for the nozzle height of 35 cm above the canopy, respectively. For the three nozzle heights, the top of the canopy received 2.8 and 4.8 times greater average spray deposits than the middle and bottom, respectively. For a boom sprayer with conventional hydraulic flat fan nozzles, spray deposits on the top of peanut canopies were 10.5 times higher than that at the middle position and 62 times higher than that at the bottom positions (Zhu et al., 2002). Therefore, spray penetration capability and spray deposition uniformity inside the taxus canopies were greatly improved with the five-port air-assisted sprayer.

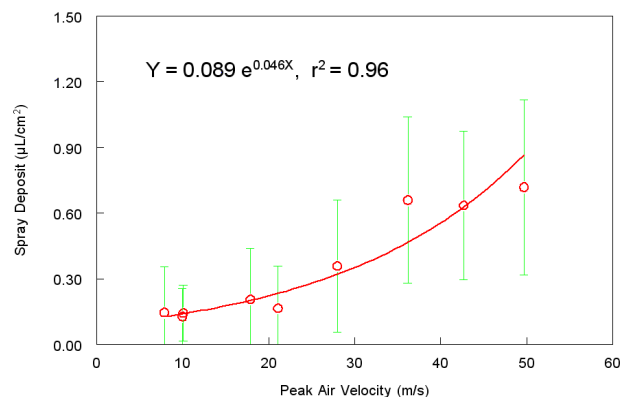
There was no significant difference in deposits at the middle of canopies between nozzle heights of 25 and 35 cm, but the deposit at the middle of canopies with the nozzle height of 15 cm was significantly higher than that at the other two nozzle heights (fig. 9). The change in nozzle height above canopies from 15 to 35 cm did not produce significant difference in spray deposition at the bottom of taxus canopies with the five-port air-assisted sprayer. The reason might be because the peak air velocities at the bottom of the canopies from the three nozzle heights were very close (table 1).

For water droplets, the critical relative velocity at which the droplet will continue to break up is given by the following equation (Lefebvre, 1989):

$$U_R = \frac{784}{\sqrt{D}} \quad (2)$$

where  $U_R$  is the critical relative velocity (m/s), and  $D$  is droplet diameter ( $\mu\text{m}$ ).

The average exit air velocity from the three five-port nozzles was 76.8 m/s. From equation 2, the largest droplet diameter from the sprayer would be approximately 104  $\mu\text{m}$  or smaller. The average spray deposit at the bottom of canopies at a nozzle height of 25 cm above the canopy was 0.127  $\mu\text{L}/\text{cm}^2$ , which was equivalent to the volume of 216 droplets of 104  $\mu\text{m}$  diameter in a square centimeter. This means that a square centimeter target area received at least 216 droplets. To effectively control insects and diseases, the number of droplets deposited on a target area was recommended as 20 to 30 droplets per square centimeter for spraying insecticides and 50 to 70 droplets per square



**Figure 10.** Effect of average peak air velocity inside the canopy on spray deposition within canopies. Error bars represent standard deviations of means.

centimeter for spraying fungicides (Syngenta, 2004). Therefore, a sufficient number of droplets was delivered to the bottom of the taxus canopies for the nozzle heights between 15 and 35 cm above canopies with the five-port sprayer at 900 L/ha application rate.

Almost equal peak air velocities at the bottom of canopies were obtained for the three nozzle heights, which corresponds to nearly equal spray deposits at the bottom of canopies for the three nozzle heights evaluated. There was good correlation between peak air velocities and average deposits inside the taxus canopies (fig. 10). For the leaf area index of 5.93, the mean spray deposit inside taxus canopies increased as the peak air velocity increased in an exponential function, with a coefficient of determination of 0.96. Strong air jets with a fan-pattern curtain from the five-port nozzle assisted in disturbing dense canopies and assisted droplets in reaching the bottom of the taxus canopy.

## CONCLUSIONS

The specially designed five-port air-assisted sprayer had great spray penetration capability and spray deposition uniformity inside taxus canopies. The average spray deposit at the bottom of canopies with the nozzle height of 25 cm above the canopy was 0.127  $\mu\text{L}/\text{cm}^2$ , which was equivalent to the volume of 216 droplets having 104  $\mu\text{m}$  diameters.

Decreasing the nozzle height from 35 to 15 cm above the top of taxus canopies did not increase spray deposits and peak dynamic air velocities at the bottom of taxus canopies for the five-port air-assisted sprayer. However, decreasing nozzle height above the top of canopies from 25 to 15 cm significantly influenced the amount of spray deposits at the middle of the canopies.

The axial air velocity model (eq. 1) agreed well with experimental values, decreasing as an equilateral hyperbolic relationship with distance from jet outlet.

There was good correlation between the amount of spray deposits and peak air velocity inside the canopy. Spray deposits inside the taxus canopies increased exponentially as the peak air velocity at the deposition sampling location increased.

For the taxus canopies, with a leaf area index of 5.93, the peak air velocity at the bottom of the canopy was reduced three times compared to the velocity at the same location outside canopies.



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## APPENDIX A: STATIC AIR VELOCITY MODEL DEVELOPMENT

Since each air jet was discharged from a circular port, air velocity at the midline of an axially symmetrical jet could be expressed from the theory of turbulent jets (Abramovich, 1963) as:

$$u_m(x) = u_0 \cdot \Delta u_m(x) \quad (3)$$

where

$$\Delta u_m(x) = \begin{cases} 1, & x \leq x_t \\ F(x), & x > x_t \end{cases} \quad (4)$$

$$F(x) = \frac{r_0 \cdot \Phi(\zeta)}{c_m \cdot (x - x_0)} \sqrt{\frac{n_2 - n_1 \cdot m}{A_1 \cdot (1 - m)^2}} \quad (5)$$

$$\Phi(\zeta) = \frac{[4 + \left(\frac{3}{\alpha}\right) + 2 \cdot \zeta] \cdot (1 + \sqrt{1 + \zeta}) + 8}{\frac{3}{\sqrt{\alpha}} \cdot \sqrt{1 + \zeta} \cdot (1 + \sqrt{1 + \zeta})} \quad (6)$$

The effective jet velocity transition length ( $x_t$ ) was defined approximately by the following equation:

$$x_t = x_0 + \frac{r_0 \cdot \Phi(\zeta)}{c_m} \sqrt{\frac{n_2 - n_1 \cdot m}{A_1 \cdot (1 - m)^2}} \quad (7)$$

The parameters in equations 5 and 7 are:

- $u_0$  = mean air velocity at the jet outlet
- $u_h$  = effective ambient air velocity outside the jet (12 m/s)
- $m = u_h/u_0$  (0.142)
- $r_0$  = jet outlet diameter (0.01905 m)
- $x_0$  = apparent main region origin relative to jet outlet, usually near zero for an axial jet (−0.1 m)

Other parameters are:

- $\alpha = A_2/A_1$  (0.519)
- $\zeta = \mu/\alpha$ ,  $\mu = m/(1 - m)$  (0.319)
- $n_1 = 0.5$
- $n_2 = 0.2$
- $c_m$  = main region empirical jet coefficient (0.22)
- $A_1 = 0.258$
- $A_2 = 0.134$

The parameters  $n_1$  and  $n_2$  are integrated measures of velocity non-uniformity and other fluid conditions at the jet outlet. The values for  $A_1$  and  $A_2$  account for the cross-sectional velocity profile in the main region of the jet. Thus, the simplified numerical air jet velocity relations were:

$$u_m(x) = \begin{cases} u_0, & x \leq 0.11 \\ \frac{0.211 \cdot u_0}{x + 0.1}, & x > 0.11 \end{cases} \quad (8)$$

## APPENDIX B: AVERAGED DYNAMIC AIR-VELOCITY TRANSIENCE DEVELOPMENT

A total of  $K$  sets of air velocity samples (vectors) were taken with  $W_{j,k}$ , where  $j = 0, 1, \dots, J$ , and  $k = 0, 1, \dots, K$ . Since velocity observations  $W_{j,k}$  were taken at time intervals  $\Delta t = 0.0005$  s, the Nyquist frequency ( $f_n$ ):

$$f_n = \frac{1}{2(\Delta t)} \quad (9)$$

was 1000 Hz, a value sufficient to ensure that  $f_n$  enclosed the frequency bandwidth of the velocity samples.

The first step in analysis of the samples was to compute a set of smoothed average velocity vectors using the “supsmooth” routine available with Mathcad (Mathsoft Engineering and Education, Inc., Cambridge, Mass.):

$$S_{j,k} = \text{smoothed}(W_{j,k})$$

The next step was to shift the smoothed velocity pulses so the peaks,  $\max(S_{j,k})$ , for each  $k$  were coincident. This was done by determining the smallest index,  $\min(j_{\max})$ ,  $k$  for the  $\max(S_{j,k})$  of each of the  $k$  vectors, giving new indices:

$$i = j - \min(j_{\max}), k \quad (10)$$

which yielded a new set of smoothed velocity transients for which the peak velocities were coincident:

$$V_{i,k} = S_{j - \min(j_{\max}), k} \quad (11)$$

It was then possible to obtain an average velocity pulse:

$$U_i = \frac{1}{k} \sum_k V_{i,k} \quad (12)$$

At this point, samples could be truncated, so that:

$$i = 0, 1, 2, \dots, N \quad (13)$$

where  $N$  must be a power of 2 to enable later transformation to the frequency domain by the fast Fourier transform (FFT).

The vectors for fluctuating velocities were calculated as:

$$w_{i,k} = W_{i,k} - S_{i,k} \quad (14)$$

The frequency spectrum for the  $k$  velocity vectors was calculated as:

$$f_{q,k} = \text{FFT}(w_{i,k}), \quad q = 0, 1, \dots, \frac{N}{2} \quad (15)$$

An average spectrum was then calculated as:

$$F_q = \frac{1}{K} \sum_k f_{q,k} \quad (16)$$

By inverse FFT (IFFT), a resultant vector of fluctuating velocity was then:

$$u_i = \text{IFFT}(f_{q,k}), \quad i = 0, 1, \dots, N \quad (17)$$

The resultant total velocity was:

$$V_{T,i} = U_i + u_i \quad (18)$$

In this study,  $K = 5$ ,  $\Delta t = 1/2000$  or  $0.0005$  s, and  $J = 13896$ .